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# EXPERIMENTAL DEMONSTRATION OF WEAVER'S MODEL OF MAGNETIC FIELDS FROM OCEAN WAVES



Andrew R. Ochadlick, Jr.
Sensors and Avionics Technology Directorate
NAVAL AIR DEVELOPMENT CENTER
Warminster, Pennsylvania 18974



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Magnetic measurements have been made above ocean waves from a stable platform at sea. The results are consistent with the theory of magnetic fields associated with ocean waves as developed by J. T. Weaver (Journal of Geophysical Research, Vol. 70, No. 8, pages 1921-1929, 1965). The theory offers the potential to reduce or eliminate ocean wave noise in MAD (Magnetic Anomaly Detection).

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## LIST OF SYMBOLS

| | |
|---|---|
| $a$ | Amplitude of ocean wave (cm) |
| exp( ) | The exponential $e = 2.718\ldots$ raised to the ( ) power (dimensionless) |
| $F$ | Magnitude of earth's magnetic field (gauss) |
| $\vec{F}$ | Earth's magnetic field vector (gauss) |
| $g$ | Acceleration due to gravity (cm/sec$^2$) |
| $h'_{\parallel}$ | Component of ocean wave's magnetic field that is parallel to the earth's magnetic field (gauss) |
| $h'_{\parallel}/a$ | Magnetic field per meter wave amplitude (nT/m) |
| $\hat{i}$ | Unit vector in +x direction |
| $I$ | Earth's field dip angle (degrees) |
| $\hat{j}$ | Unit vector in +y direction |
| $\hat{k}$ | Unit vector in +z direction |
| $s$ | Height above mean sea surface (cm) |
| $x$ | x coordinate (cm) |
| $y$ | y coordinate (cm) |
| $z$ | z coordinate (cm) |
| $\sigma$ | Conductivity of sea water (emu) |
| $\pi$ | 3.14 . . . |
| $\theta$ | Eastward inclination of the direction of wave propagation measured from the magnetic meridan |

Comment on Units: The symbols used are those of other authors. To preserve clarity, they are shown with the units used by those authors. The final results of this report and all diagrams in this report use mks units with the SI convention that T(tesla) = 1 weber/m$^2$ so that $10^{-5}$ gauss (= 1 gamma) = 1 nT. To avoid confusion with the standard symbol s used for altitude, the abbreviation used for time in seconds is sec instead of s.

## LIST OF ACRONYMS

| | |
|---|---|
| AN/ASQ-81(V) | Designation of MAD Sensor |
| MAD | Magnetic Anomaly Detection |
| NAVAIRDEVCEN | Naval Air Development Center |
| NOSC | Naval Ocean Systems Center |
| SUNYA | State University of New York at Albany |

# EXECUTIVE SUMMARY

## INTRODUCTION

The purpose of this report is to compare an existing theoretical model of the magnetic fields generated by ocean waves developed by Weaver (1) with an experimental measurement of such magnetic fields.

"Ocean wave noise" is the term used in the MAD (Magnetic Anomaly Detection) literature to describe the magnetic fields associated with ocean surface waves that are capable of lowering MAD performance. The source of the ocean wave noise is electric currents flowing in the sea due to the motion of the sea by waves in the presence of the earth's magnetic field. The process of generating the current is similar to the current producing process of an electric generator. The net result being that an electric current is produced in the sea that has an associated magnetic field.

Any form of magnetic noise that exceeds the MAD sensor sensitivity can reduce MAD capability. At an altitude of 150 m above the ocean, ocean waves with an amplitude of 0.5 m (1 m peak-to-peak) and a period of 15 sec will produce a peak-to-peak magnetic noise that is about a factor of ten above the MAD sensor sensitivity of 0.01 nT.

## SUMMARY OF RESULTS

The theoretical value of ocean wave noise was found to be in good agreement with the measured value. (The percent difference between the theoretical and the averaged measured value is less than 6%.)

## CONCLUSIONS

The theoretical model developed by Weaver to predict the magnetic fields of surface ocean waves is supported by an experimental measurement.

## RECOMMENDATIONS

1. Methods to satisfactorily implement Weaver's ocean wave model into a MAD signal processing scheme to reduce or eliminate ocean wave noise should be developed.

2. Data collection of ocean wave noise with an airborne magnetometer should be initiated to support potential signal processing schemes of ocean wave noise removal.

## BACKGROUND ON MAD NOISE

Ocean wave noise is one of several noise types detectable with the AN/ASQ-81(V) MAD sensor. (See (2) for details of sensor.) These noise types are briefly discussed below as to their origin and their negative effect on MAD.

Environmental types of magnetic noise that can limit MAD capability include geologic, geomagnetic and ocean wave noise. Geologic noise (3) is the magnetic anomalies in the earth's magnetic field caused by crustal magnetization. Geomagnetic noise (4,5) is the result of a complex solar terrestrial relationship. It originates in electric currents in the earth's upper atmosphere that cause temporal variations in the earth's magnetic field. The currents are due to an interaction of solar particles and solar electromagnetic radiation with the earth's upper atmosphere. Ocean wave noise is a magnetic field originating from electric currents induced in the sea and is elegantly described by Weaver's (1) theoretical formulas. The currents are a result of the wave motion of the sea, a conducting medium, moving across the magnetic field lines of the earth. The process of generating the current is similar to the current producing process of an electric generator.

Along with the environmental type noise, MAD is also influenced by platform noise and gradient noise. Platform noise is a result of incomplete reduction of the platform's magnetic field. Horizontal magnetic field gradients can produce noise during a turn. Vertical gradients can produce noise during an altitude change.

The sensor noise is the basic noise level of the MAD sensor. If any of the noise sources are in the bandpass of the MAD sensor and exceed the basic sensor noise level, it will be detected with a resultant loss in MAD capability due to a reduced signal-to-noise ratio.

Kraichman (6) lists magnetic noise contributions in the following order based on the percent of time each is present enough to influence MAD performance in important operating areas:

1. geologic noise
2. aircraft noise

3. ocean wave noise
4. geomagnetic noise

The use of models to reduce any of these noise sources will offer an improved MAD performance by increasing the signal-to-noise ratio. Such models must be verified in the real world before being implemented. This report deals with an experimental verification of a theoretical ocean wave noise model developed by Weaver (1). The following reviews Weaver's model, the experimental method to verify it at sea, and an analysis and discussion of the results.

## REVIEW OF WEAVER'S MODEL

The geometry used by Weaver to calculate the magnetic field induced by the motion of the seawater across the earth's magnetic field is shown in Figure 1. The ocean wave shown corresponds to a gravity wave of angular frequency $\omega$ moving in the +x direction. The amplitude of the wave above and below the mean free surface is represented by a. The +z axis is taken vertically down and the +y axis is oriented parallel to a line along the waves crests in a direction to form a right-handed rectangular coordinate system. The angle between the direction of magnetic north and the +x axis measured in an eastward direction to the +x axis is represented by $\Theta$. The earth's magnetic field vector is represented by $\vec{F}$, and is taken as constant in time and space. It lies in planes perpendicular to the x y plane and parallel to the direction of magnetic north. The angle that $\vec{F}$ makes with the direction of magnetic north is the earth's field dip angle, I. The conductivity of the sea water is represented by $\sigma$.

Details of the theoretical formulation can be found in (1). Briefly, Weaver makes the usual assumptions that the seawater is incompressible and the velocity of seawater due to a surface wave is irrotational. This allows the introduction of a velocity potential that satisfies Laplace's equation. The solution of Laplace's equation results in a velocity potential that describes a pure gravity wave. Weaver then obtains the velocity vector of the seawater from

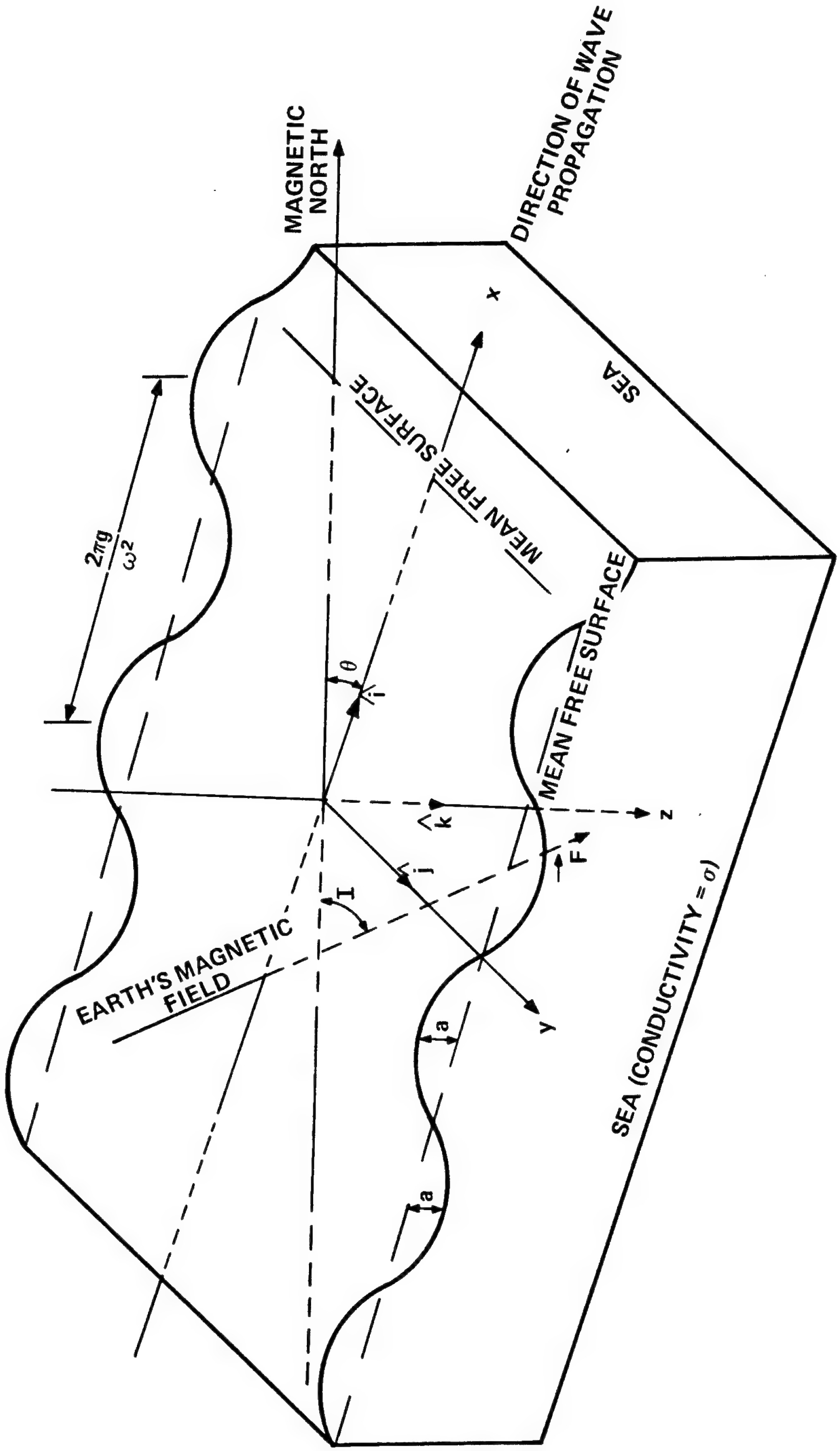


FIGURE 1 - geometry of Weaver's ocean wave model (from Reference (1))

the velocity potential. The vector cross-product of the velocity vector and the earth's magnetic field vector represents an induced electric field vector in the seawater. Using the induced electric field vector in Maxwell's equation, Weaver obtains a solution for the magnetic field vector after applying the boundary conditions. He then obtains approximate forms of the solution by making valid assumptions. The final step determines the component of the magnetic field, induced by the seawater, that is parallel to the earth's magnetic field vector. As pointed out by Weaver, that is the component measured by a total field magnetometer. In Weaver's notation the amplitude of this component is

$$h'_{\shortparallel} = (\pi a \sigma F g/\omega)\,(\sin^2 I + \cos^2 I \cos^2 \Theta)\,\exp(-s\omega^2/g) \qquad (1)$$

where

- $h'_{\shortparallel}$ : amplitude of component of ocean wave's magnetic field parallel to the earth's magnetic field (gauss)
- $a$ : amplitude of ocean wave (cm)
- $\sigma$ : conductivity of seawater (emu)
- $F$ : magnitude of earth's magnetic field (gauss)
- $g$ : acceleration due to gravity (cm/sec$^2$)
- $\omega$ : angular frequency of ocean waves (radians per sec)
- $I$ : earth's field dip angle (degrees)
- $\Theta$ : eastward inclination of the direction of wave propagation from the magnetic meridian (degrees)
- $s$ : height above sea (cm).

This is the expression to be compared with the experimental results obtained with a total field magnetometer. It is plotted in Figure 2 for various parameters. Following Weaver (1), it is plotted as magnetic field per meter wave height vs. altitude. Notice that the magnetic field is dependent on the period of the waves and on their amplitude. In the next section, an experimental method used to determine $h'_{\shortparallel}$ is explained.

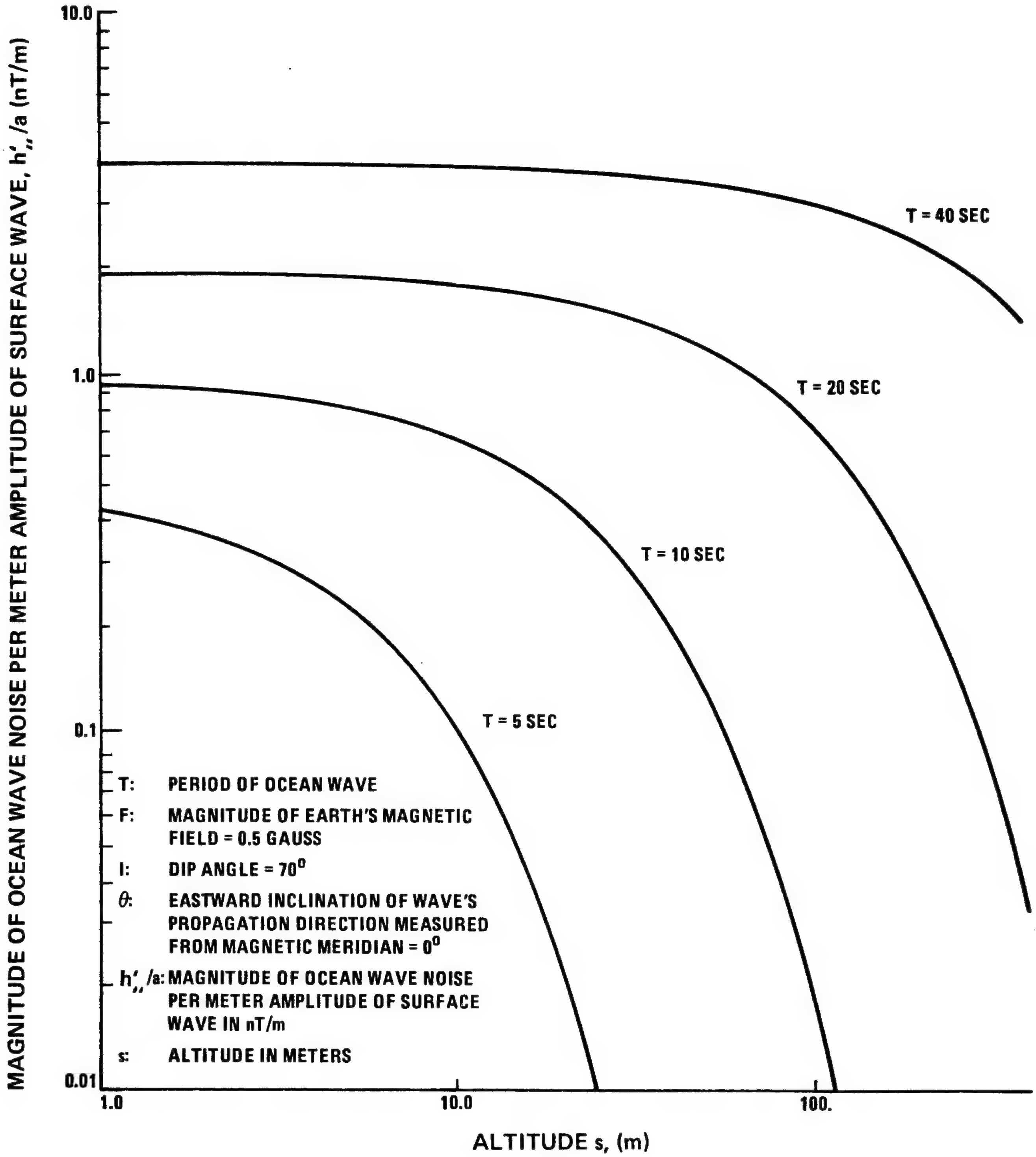


FIGURE 2 - plot of Weaver's ocean wave equation

## EXPERIMENTAL METHOD

In order to test the theoretical model, the height of the ocean waves and the magnetic field above the ocean were measured simultaneously from the NOSC (Naval Ocean Systems Center) oceanographic tower located about 1.61 km off the San Diego coast in about 20 m of water. The oceanographic tower was equipped with a non-magnetic boom of about 20 m in length for magnetic measurements away from the tower. A photograph of the tower and boom arrangement is shown in Figure 3.

In his paper (1), Weaver points out that the motion of a sea platform makes reliable magnetic measurements over the ocean surface difficult. Fortunately, the motion of the platform was not a problem in this experiment. The stability of the boom-tower arrangement had been previously considered (7) to offer a satisfactory platform for the measurements of ocean wave noise. This was confirmed by sensitive tilt measurements (8) of the boom-tower combination. The boom orientation at the magnetic sensor is stable to 5 seconds of arc (9). Magnetic measurements of the tower can be found in (10).

The magnetic field measurements of the ocean waves, $h'_{\parallel}$, were made as a function of time with a total field magnetometer (the AN/ASQ-81(V) MAD sensor) located near the end of the boom. The magnetometer's sensitivity is 0.01 nT ($10^{-7}$ gauss) in a 0.04- to 0.60-Hz bandpass. The wave height measurements, a, were obtained as a function of time from a pressure transducer located below the ocean surface. The angular frequency, $\omega$, of the ocean wave was determined from the period of the wave height oscillation. The analog signals of both the pressure transducer (wave height) and the magnetometer output were displayed simultaneously on a paper chart recorder. An example is shown in Figure 4. The correlation of the magnetometer output with the transducer output is apparent. The slight phase shift is due to a spatial separation of the presure transducer with respect to a point directly below the magnetometer and the different filtering used on both instruments.

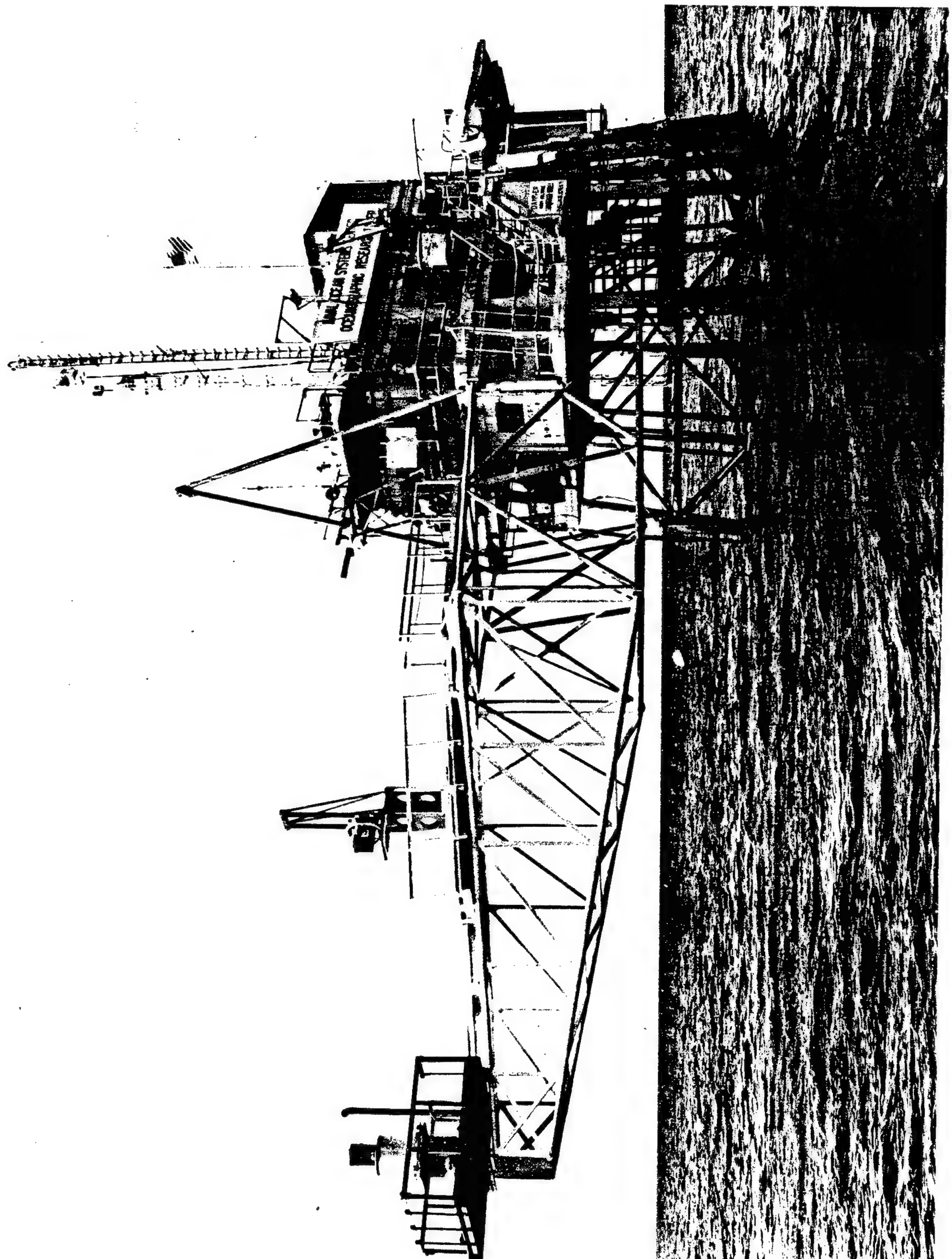

FIGURE 3 - photograph of NOSC's oceanographic tower

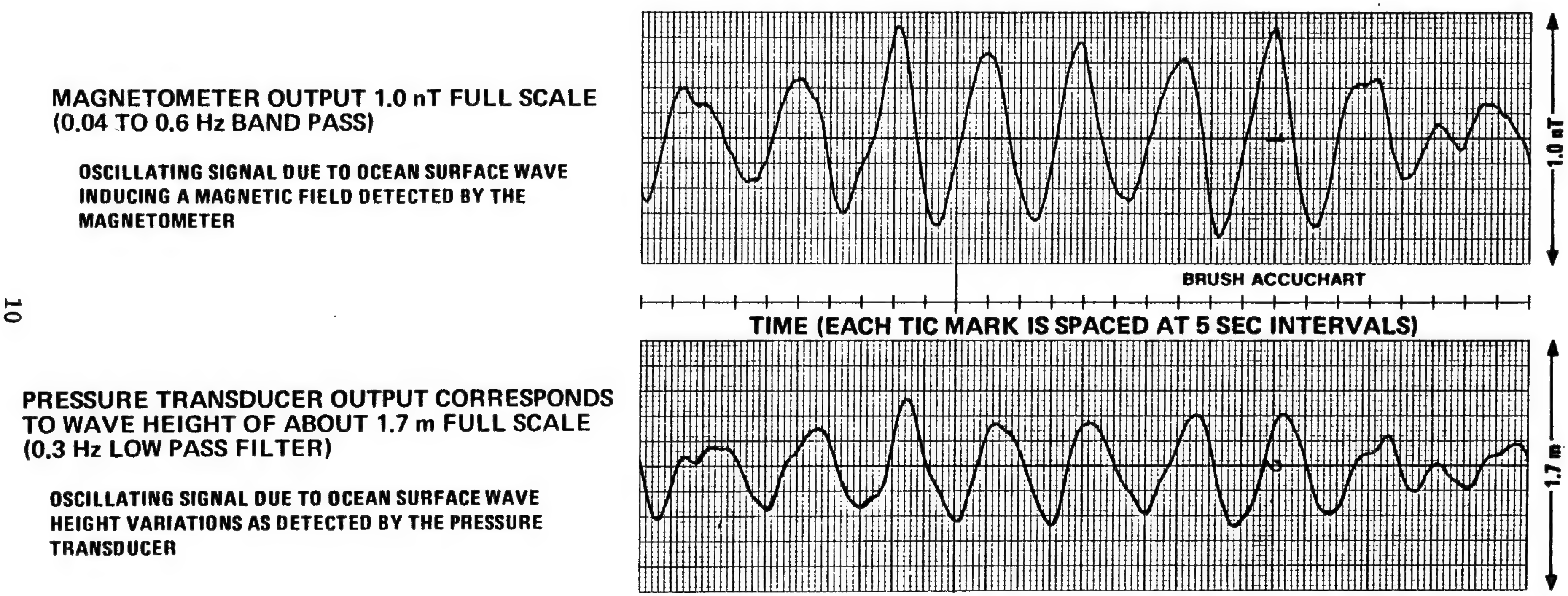


FIGURE 4 - example of the correlation of the magnetic fields induced by ocean waves with wave height (part of original chart record)

## ANALYSIS OF EXPERIMENTAL RESULTS

Following the procedure of Maclure et al. (11), values of the magnetic field per meter amplitude of the ocean wave were determined for the dominant wave period during the measurement period that lasted from 0900 hours PDT June 1, 1978 until 0700 hours PDT on June 2, 1978. The dominant frequency was found to be 15 sec. Choosing only data at this frequency that was, in addition, represented by smooth and sinusoidal oscillations of at least three complete oscillations of the same amplitude, resulted in a total of seven data points. The average of the seven data points resulted in an experimental value of $h'_{\parallel}/a = 0.88$ nT/m (magnetic field per meter wave height) with a standard deviation of 0.05 nT/m. In the next section Weaver's theoretical value is determined.

## WEAVER'S THEORETICAL VALUE

The parameters in Weaver's equation (1) during the relevant time of the experiment were:

$\omega = 2\pi\ (1/15)$ rad/sec

$I = 58^{\circ}$

$\theta = 90^{\circ}$

$\sigma = 4.0 \times 10^{-11}$ emu

$F = 0.492$ gauss

$g = 980\ \mathrm{cm/sec}^2$

$s = 600$ cm

Substituting these quantities into equation (1), solving for $h'_{\parallel}/a$, and converting into mks units results in $h'_{\parallel}/a = 0.93$ nT/m. In the next section this value is compared with the experimental value.

## COMPARISON OF EXPERIMENTAL AND THEORETICAL RESULTS

Weaver's theoretical formula, equation (1), predicts a value of $h'_{\parallel}/a = 0.93$ nT/m for the experimental conditions. The experimental measured value has been shown to be $h'_{\parallel}/a = (0.88 \pm 0.05)$nT/m. The theoretical value falls within the uncertainty of the experimental value. Furthermore, the theoretical value agrees to within better than 6% of the average experimental value. A discussion of certain aspects of the experiment, theory and results is given in the following discussion section.

## DISCUSSION

The agreement between theory and this experiment was tested for only one set of parameters such as a specific value of altitude, dip angle, magnitude of earth's magnetic field, wave period and direction of wave propagation. This is because the experiment was performed at only one location, resulting in the specific value for the magnitude of the earth's field and dip angle. Furthermore, nature provided only one usable wave frequency and one direction of wave propagation. Additional experimental work could be performed with an airborne magnetometer and data collection system including supporting ground truth data taken at various locations to change the parameters.

It should be mentioned that airborne magnetometer data of ocean wave noise will undergo an apparent frequency change due to the horizontal velocity of the aircraft. Weaver's paper (1) includes the equation (his equation (29)) to describe the frequency shift.

The results of Weaver's ocean wave model (1) are in good agreement with 1) the experimental results of Maclure et al. (11) in deep water obtained below the ocean, and 2) the results presented in this report obtained above the ocean. Hence, the application of Weaver's ocean wave model to the removal of ocean

wave noise from MAD data by signal processing techniques is valid and offers the potential to reduce and possibly eliminate ocean wave noise. Such processing is envisioned to involve appropriate wave profile measurements from the MAD aircraft. The wave profile would be used in Weaver's model to determine the expected ocean wave noise. This expected value could then be subtracted from the MAD data. Technology exists (for example, reference 12) to provide a low flying aircraft with the ocean wave profile.

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